Early Student Support for Process Study of Oceanic Responses to Typhoons

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LONG-TERM GOALS

Our long-term scientific goals are to understand the upper ocean dynamics, to understand the coupling between the ocean and atmosphere via air–sea fluxes, and to quantify the mechanisms of air–sea interactions. Our ultimate goal is to help develop improved parameterizations of air–sea fluxes in ocean–atmosphere models and parameterizations of small-scale processes in the upper ocean and the stratified interior.

OBJECTIVES

Tropical cyclones derive energy from the ocean via air–sea fluxes. Oceanic heat content in the mixed layer and the air–sea enthalpy flux play important roles in determining the storm's maximum potential intensity, structure, energy, trajectory, and dynamic evolution. The most energetic oceanic responses to tropical cyclone forcing are surface waves, wind-driven currents, shear and turbulence, and inertial currents. Quantifying the effect of these oceanic processes on air–sea fluxes during tropical cyclone passage will aid understanding of storm dynamics and structure. The ocean's recovery after tropical cyclone passage depends upon small- and meso-scale oceanic processes in the storm's wake region. These processes are the least understood primarily because of the paucity of direct field observations under passing tropical cyclones; as a consequence, there are large uncertainties in air–sea flux parameterizations in extreme wind regimes.

The primary objective of this grant is to support a graduate student, Andy Hsu. He will pursue a PhD degree with the focus on the process study of oceanic responses to tropical cyclones in the western Pacific observed during the ITOP intensive observation period using direct observations and numerical model simulations.

APPROACH

During the 2010 typhoon season (the intensive observation period of ITOP), two arrays of seven EM-APEX floats each were air-launched in front of typhoons Fanapi and Megi; the floats transmitted near-real time observations of velocity, temperature, salinity, and GPS position via Iridium satellite. The

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data from EM-APEX floats are used for the study of oceanic responses to Typhoons. PWP3D model is used to facilitate the process study.

WORK COMPLETED

The first-year graduate student, Andy Hsu, attended ONR ITOP workshop in Taiwan in April 2012. The analysis results from the EM-APEX floats data were presented. He has been working on the data analysis of ITOP EMAPEX observations and performing PWP3D model simulations.

RESULTS

Typhoon Fanapi study

Strong near-inertial and subinertial jet were induced by Typhoon Fanapi. The EM-APEX float 4913a was located near the maximum inertial resonant region; the float's velocity field is decomposed into tidal, inertial, and subinertial motions. The decomposition is calculated on the isopycnal coordinate to prevent the artificial results from the initial pumping. The zonal velocity at subinertial frequency shows that a subsurface subinertial jet is fully developed one day after the Typhoon Fanapi pass (Fig. 1, top panel). The subinertial jet may play an important role in trapping the near-inertial waves. Near-inertial energy propagates downward initially right after Typhoon Fanapi but remains in the thermocline for about 3 days, instead of penetrating deeper (Fig. 1, lower panel). There are two possible explanations for the persistent near-inertial wave in the thermocline. First, the positive geostrophic vorticity associated with the subinertial jet induced by Typhoon Fanapi stopped the near-inertial wave. It had lower intrinsic frequency and could not propagate freely [*Kunze*, 1985]. Second, the slowly propagating high-mode, near-initial waves were left behind after the fast propagating, low-mode waves left the site [Gill, 1983].

The pre-Fanapi vorticity field from the Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data shows there were several background eddies, two cyclonic eddies, and one anticyclonic eddy (Fig. 2, top left panel). The vertical structure of the background vorticity from the array of EM-APEX floats shows similar pattern as AVISO with strong negative vorticity –0.2 – –0.4 f_o at the subsurface (Fig. 2, top right panel), where f_o is the local inertial frequency. The subinertial jet induced by Typhoon Fanapi shows positive vorticity 0.3 f_o at the eye of Fanapi and negative vorticity (–0.1 f_o) at the background (Fig. 2 bottom panel). Because of the asymmetric wind field, the positive vorticity extends to the right of the Fanapi track with depth. The equatorward near-inertial waves may be reflected due to positive vorticity and the poleward near-inertial waves may be trapped due to inertial frequency increases with latitude [Garrett, 2001].

The PWP3D model was used to simulate the ocean thermal response in Sanford et al. [2011]. Their model results agreed with the EM-APEX float data by showing temperature decreasing 2.5°C in the mixed layer during Hurricane Frances. A similar simulation was made for Typhoon Fanapi. Our simulation shows there is 1.5°C unpredicted cooling during Fanapi (Fig. 3). There are several possible causes for the discrepancy, such as inaccurate initial conditions, missing surface heat and buoyancy fluxes in the model, float advection, and background eddy and evolution. We will investigate the discrepancy further.

Typhoon Megi study

The momentum budget method of Sanford et al. [2011] is used to calculate the drag coefficient. The equation

$$\int_{-H}^{0} \boldsymbol{u}_t + f\boldsymbol{k} \times \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \boldsymbol{u} \nabla \cdot \boldsymbol{u} \approx \frac{\boldsymbol{\tau}_w}{\rho_0} + \frac{\nabla \cdot p}{\rho_0}$$

is evaluated using a PWP3D model to determine how well the first 2 terms, which can be easily measured using EM-APEX floats, can estimate the drag. $\boldsymbol{u}_t$ is the time derivative of velocity; $f\boldsymbol{k} \times \boldsymbol{u}$ is the Coriolis acceleration; $\boldsymbol{u} \cdot \nabla \boldsymbol{u}$ is the advection term; $\boldsymbol{u} \nabla \cdot \boldsymbol{u}$ is the divergence term; $\boldsymbol{\tau}_w$ is the surface wind stress; and $\frac{\nabla \cdot p}{\rho_0}$ is the pressure gradient term. The integration depth is from the surface to 150 m. The model is driven using a storm wind model and a drag coefficient from Powell [2003]. We test whether the drag computed via momentum budget is the same as that input to the model. There is no other external forcing inside the model except for hurricane wind. Fig. 4 shows the results at a data point 32 km on the left side of the track. Most of the surface stress comes from the linear term: $\boldsymbol{u}_t + f\boldsymbol{k} \times \boldsymbol{u}$, before the hurricane passed. The pressure gradient term is not important until the hurricane passed. The advection and divergence terms are relatively small compared with others. We compare actual wind stress in the model and the wind stress derived via momentum budget in Fig. 4 (f). The difference is very small. The bulk formula is $\tau_w = C_d U_{10}|U_{10}|$. C_d is the drag coefficient, and U_{10} is wind speed at 10 m. If we calculate the drag coefficient by only linear terms, it does not differ from the actual wind stress before the hurricane passed, as in Fig. 4 (i). This gives us confidence that the EM-APEX data can be used to estimate drag, at least for the first part of the storm.

IMPACT/APPLICATION

Tropical cyclones cause strong oceanic responses, e.g., surface waves, inertial waves, and a deepening of the surface mixed layer. To improve the modeling skill of oceanic responses to tropical cyclones and the prediction of tropical cyclones, we need to understand the small-scale processes responsible for the air–sea fluxes and interior oceanic mixing, and the meso-scale oceanic processes that modulate the background oceanic heat content. The ITOP field experiment provides direct observations of oceanic responses forced by tropical cyclones and the ocean's recovery, as well as aid understanding of the dynamics of small- and meso-scale oceanic processes. These observations will help improve the prediction skill of oceanic and atmospheric models in high wind regimes.

RELATED PROJECTS

Study of Kuroshio Intrusion and Transport Using Moorings, HPIES, and EM-APEX Floats (N00014-08-1-0558) as a part of QPE DRI: The primary objectives of this observational program are 1) to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), 2) to identify the generation mechanisms of the Cold Dome often found on the SECS, 3) to quantify the internal tidal energy flux and budgets on the SECS and study the effects of the Kuroshio front on the internal tidal energy flux, 4) to quantify NLIWs and provide statistical properties of NLIWs on the SECS, and 5) to provide our results to acoustic investigators to assess the uncertainty of acoustic predictions. Results of this DRI program will help understand oceanic physical

processes on the southern East China Sea, e.g., the cold dome. Typhoons may modulate the Kuroshio, the Kuroshio intrusion, and other oceanic processes that result in cold pools on the continental shelf of the southern East China Sea.

PUBLICATIONS (wholly or in part supported by this grant)

Mrvaljevic, R.K., P.G. Black, L.R. Centurioni, Y.-T. Chang, E.A. D'Asaro, S.R. Jayne, C.M. Lee, R.-C. Lien, I.-I. Lin, J. Morzel, P.P. Niiler (deceased), L. Rainville, and T... Sanford. 2012. Observations of the cold wake of Typhoon Fanapi. *Geophys. Res. Lettr.* [submitted, referred]

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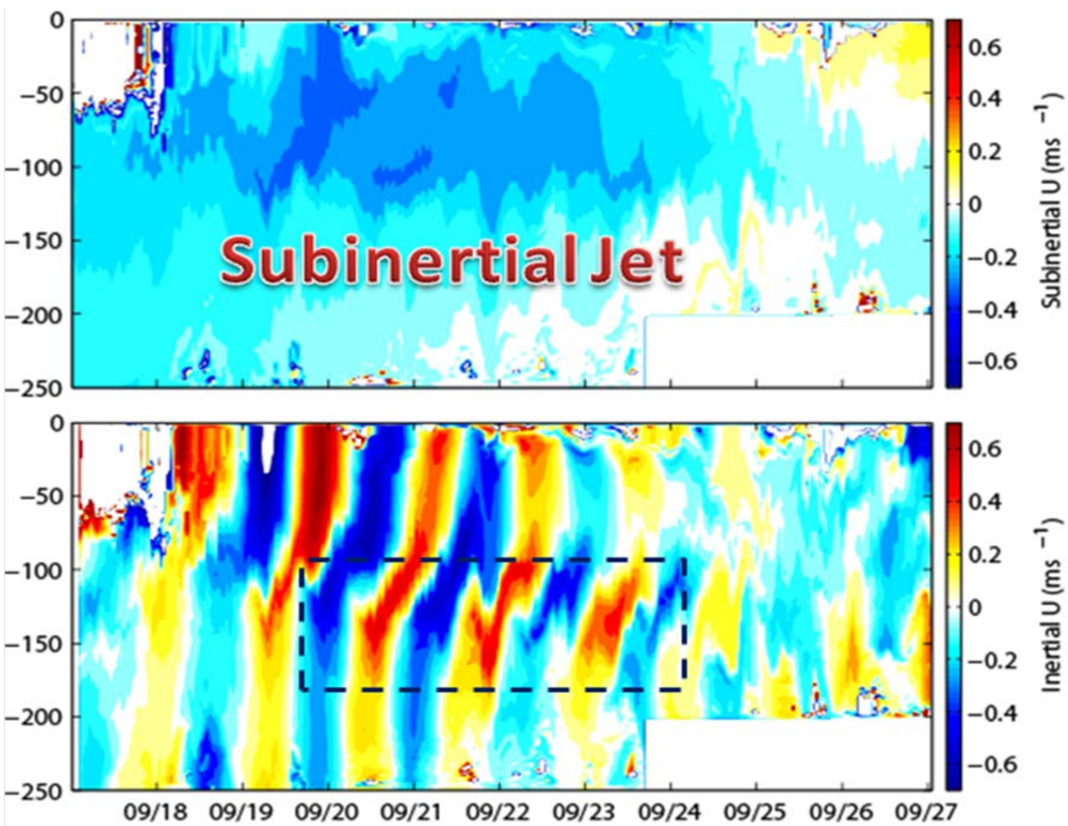

Figure 1. The zonal velocity contours at subintertial (top panel) and inertial frequcies (bottom panel) from EM-APEX float 4913a. The decomposition into the tide, inertial current, and subinertial current, is calculated on the ispopycnal coordiate. A strong subinertal jet develops one day after the Fanapi pass (upper panel). Near-inertial energy propagates downward initially, but remains in the thermocline ~3 days after the Fanapi pass (lower panel). The location of EM-APEX 4913a is shown in Fig. 2, top-left panel (blue circle).

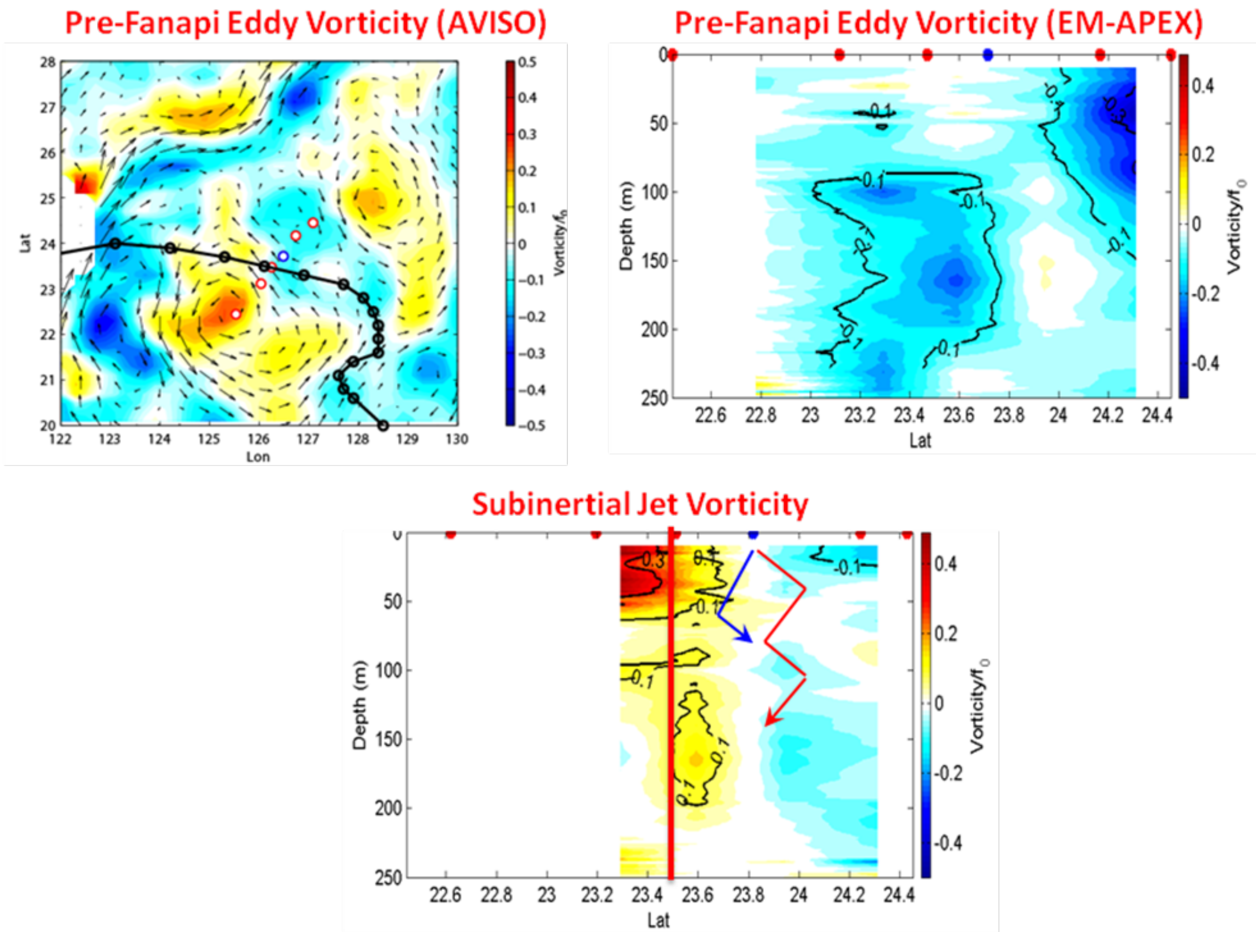

Figure 2. Top-left panel is the pre-Fanapi surface vorticity field from AVISO (the black circles indicate the best track of Typhoon Fanapi, the blue circle indicates the location of EM-APEX float 4913a, the red circles indicate the locations of other EM-APEX floats). Top-right panel is the vertical structure of the vorticity field calculated using observations of the array of EM-APEX floats (the float locations are marked on the top) before the arrival of Fanapi. Bottom panel is the subinertial jet vorticity from EM-APEX float observations after the Fanapi pass. The thick red line indicates the center of the Typhoon Fanapi, the thin blue and red lines indicate the possible mechanisms of reflecting and trapping of the equatorward and poleward near-inertial waves.

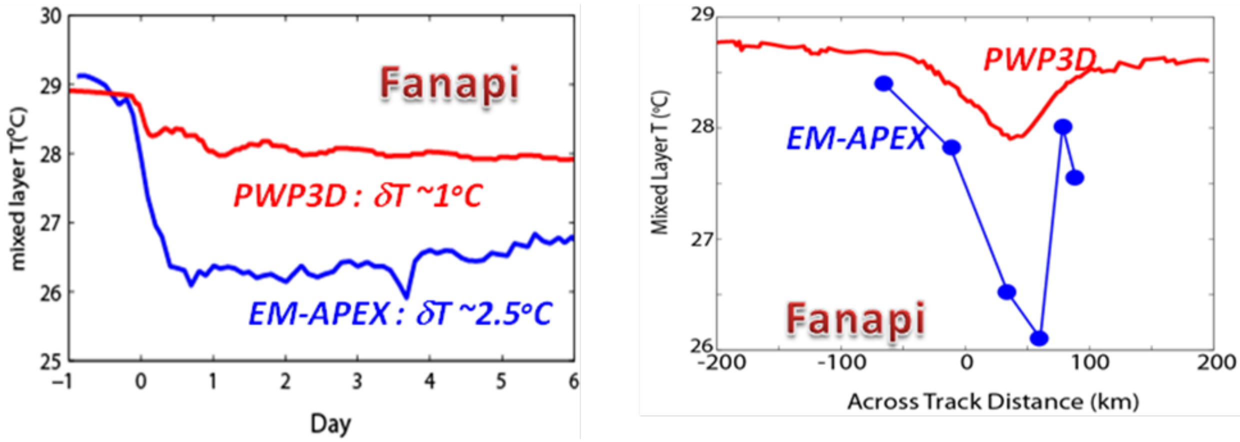

Figure 3. Left panel is the evolution of the mixed layer temperature from the EM-APEX float (blue curve) and the prediction of PWP3D model (red cure) during Typhoon Fanapi. The time is referenced to the time of Fanapi's arrival. Right panel is the spatial variation of the mixed layer temperature across the track of Typhoon Fanapi after1.7 days of Fanapi pass.

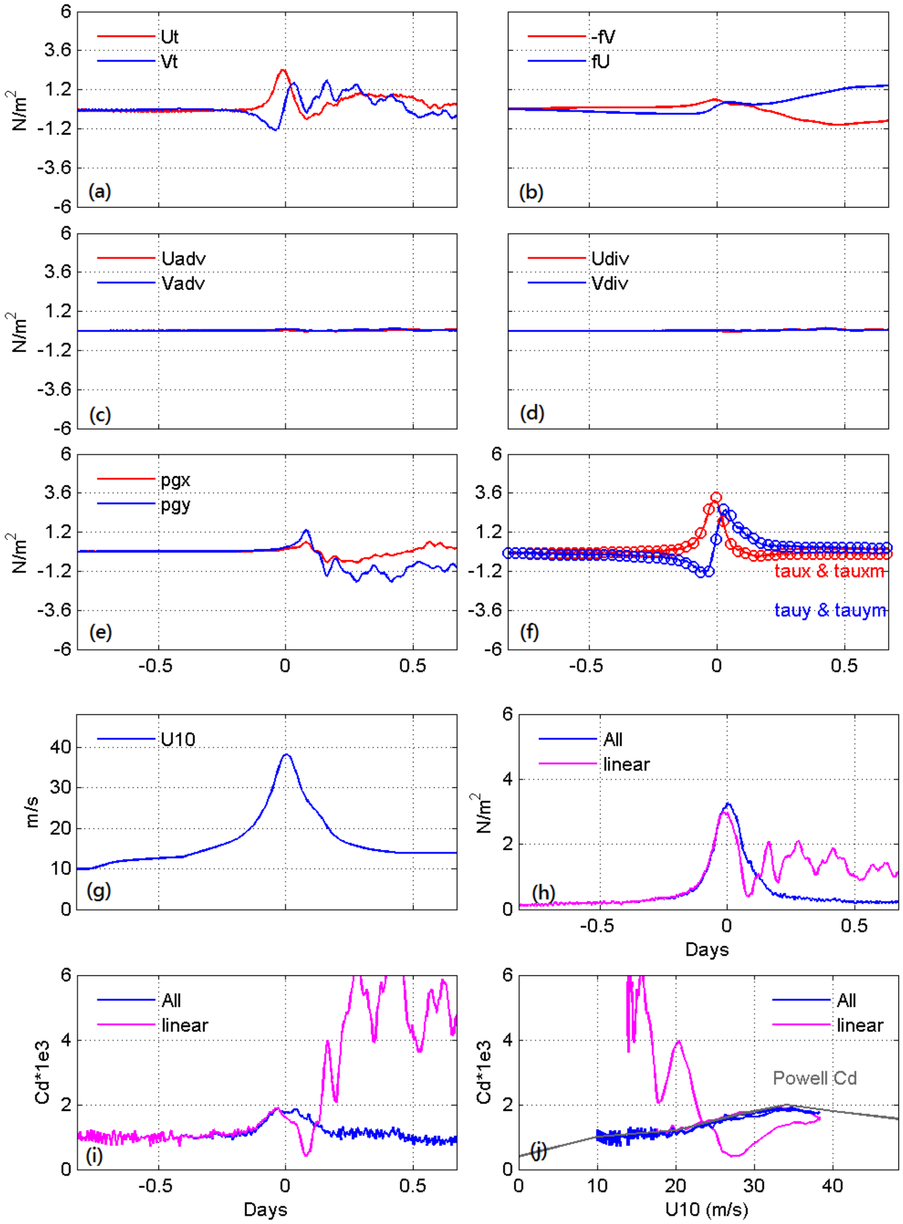

Fig. 4 The data point in PWP3D at 32 km on the left of Typhoon Megi track. (a) The time derivatives of velocity; (b) the Coriolis acceleration; (c) the advection term; (d) the divergence term; (e) the pressure gradient term; (f) the solid line is the wind stress derived from momentum budget (the sum of (a)~(e)), and the circle is the actual wind stress in the model; (g) U_{10}; (h) the blue line is the wind stress calculated from all the terms, and the pink line is only from linear term; (i) the change of C_d with time. The blue line is C_d from all the terms, and the pink line is from linear terms; (j) Rewrite (i) as the function of U_{10}. The black line is the Powell's function in 2003.

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